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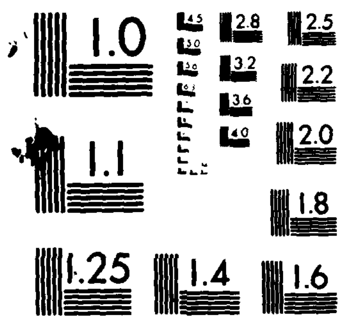

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Digraph Frequency Effects in Skilled Typing

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Abstract

These studies use both discontinuous and continuous typing paradigms in investigating digraph frequency effects in skilled typing. Previous studies that controlled for hand use showed no digraph frequency effects. With more rigorous controls we found very reliable digraph frequency effects, suggesting that, with experience, typists develop multi-character response units. Videotape analysis indicated at least one way such response units can potentially coordinate and facilitate performance.

Digraph Frequency Effects in Skilled Typing

Table of Contents

We thank the LNR Research Group, and particularly Don Norman, Don Gentner, and Craig Will, for their contributions to this work. We also thank the typists who participated in the studies, Janice Graham for helping with data analysis, Patty Haden and Eileen Conway for helping to prepare the manuscript, and Jeffrey Miller for commenting on it.

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Digraph Frequency Effects in Skilled Typing

Frequency and Response Unit Size in Performance

What changes with practice in the acquisition of a motor skill? In this paper, we argue that skilled typists have replaced the single-letter response units of the novice with multi-letter response units that result in greater efficiency. We also present data that screen out certain associative and hierarchical models.

The idea that the learner increases the size of perceptual and motor units with experience is not new. Bryan and Harter (1897; 1899) concluded that student telegraphers ascend a hierarchy in receiving Morse code, and believed that the same is true in sending Morse code. They argued that first individual dots and dashes, then letters, and finally words and phrases are handled as units. Lashley (1951) proposed a hierarchical response organization as an alternative to associative chaining, which, he noted, cannot explain our ability to embed a given element in different contexts.

Hierarchies of phoneme-syllable-word (for speech) and letter-syllable-word (for typing) have been proposed (e.g., Lashley, 1951; Fromkin, 1971; Terzuolo & Viviani, 1980). But the evidence behind all these models has subsequently been shown to yield to alternative explanations (Keller, 1958; Wickelgren, 1969; Rumelhart & Norman, 1982; Gentner, 1981b). Wickelgren (1969) outlined associative models that he felt were viable. In the context-sensitive associative model he favored for speech, the phonetic elements for the word baby are /#ba/ bab/ abee/ /bee#/, rather than /b/ /a/ /b/ /ee/. (The element /#ba/ represents the phoneme /b/ with a pause before (/#/) and /a/ following. Neighboring elements are associated by shared features. The complete set of such units is not unreasonably large, Wickelgren argued.

Rumelhart and Norman (1982) developed a simulation model of transcription typing based on a control scheme similar to that proposed by Estes (1972) to model serial ordering in memory recall. The model has two levels of output representation: word and letter. "Keypress schemata" for each letter are activated. Correct serial ordering is achieved through inhibitory links from each active letter to all the letters that follow it.

The Wickelgren (1969) and Rumelhart and Norman (1982) models perform well with nothing between the word and individual phonemes or keypress schemata. Once the set of basic elements is acquired, they need not be replaced or transformed. The following studies argue that the initial set of basic response units needs to be supplemented or replaced by more complex response units, and that these complex responses are more than an associative linking of simpler units.

The first study follows closely the procedure of Sternberg, Knoll, and Wright (1978), in which skilled typists are presented with one word or letter string at a time. We found that peak performance can be maintained in typing letter strings that do not form words, as long as the digraph composition of such strings is equivalent to that of words. However, a clear deterioration in performance occurs with letter strings made of lower frequency digraphs.

In the next two studies, we focus on performance in a normal typing situation. The second study shows that digraph frequency effects are also found when skilled typists transcribe normal text. All else controlled for, high-frequency digraphs are typed more quickly than low-frequency digraphs. This effect is widespread, but stronger with sequences typed by two fingers of the same hand (2F).

In this work we use the terminology of the LNR Research Group (in press). In particular, 2F (two-finger) describes a sequence of letters typed by two fingers of the same hand. This is in contrast to 1F (one-finger), a sequence typed by a single finger, and 2H (two-hand), a sequence typed using both hands. 1H, within-hand, is used when that distinction is sufficient.

In the third study we describe a videotape analysis of skilled transcription typing. This study demonstrates that changes in the pattern of motor responses can facilitate performance. For the 2F sequences observed, the motor pattern for a letter sequence has been optimized in a manner that suggests that a new response unit has been formed.

Typists begin by learning individual letters. We propose that they form larger response units with practice, and that the frequency of exposure to digraphs and larger letter combinations influences this development of multi-character units. Although digraph frequency effects might be consistent with a simple hierarchical model, or with a model positing varying associative strengths among elements, the videotape analysis suggests a model in which the basic motor units are multi-letter sequences.

Several studies of skilled typing looked for digraph frequency effects (Fox & Stansfield, 1964; Shaffer & Hardwick, 1968; Sternberg, Knoll, & Wright, 1978; Terzuolo & Viviani, 1980). These studies yielded mixed results. Most contained possible confoundings. The most critical confounding is that of frequency with hand: high-frequency digraphs are likely to be across-hand (2H). The keyboard has been designed to break high-frequency digraphs apart, placing the separate letters on opposite sides of the keyboard (Beeching, 1974). Four of the 5 most frequent letter-letter digraphs and all of the 5 most frequent digraphs including a space are 2H. (The statistics are from Mayzner & Tresselt, 1965 for letter-letter digraphs, and from our text for letter-space and space-letter digraphs.) A discontinuous typing study that controlled for hand by looking separately at within-hand and across-hand digraphs (Sternberg, Knoll, & Wright, 1978), and a continuous typing study with the

same control (Fox & Stansfield, 1964), found no effect of digraph frequency within each category.

The Digraph Frequency Effect in Discontinuous Typing

Following Sternberg, Knoll, and Wright (1978) we constructed two sets of stimuli. One set consists of letter strings normally typed with the fingers of one hand (1H). The other set consists of letter strings that alternate between hands (2H).

Within the 1H and the 2H sets, there are three stimulus categories. One consists of 1H and 2H English words 3 to 6 letters long. From these, we derived two categories of nonlexical items. One ("pseudowords") was constructed by recombining letters in such a way as to preserve, as much as possible, the digraph composition found in the words. (Word length and motor composition, 1H versus 2H, are maintained.) The final category ("nonwords") was constructed by pseudorandomly recombining letters, preserving word length and motor composition.

The derivations are not perfect, with the result that some letters appear slightly more often in one stimulus category or another. Similarly, the average digraph frequency of the words and pseudowords was not exactly the same. Table 1 presents the average frequencies for the various stimulus categories, based on a 25,000 word dictionary of English. The difference in single-letter frequency between stimulus categories is very small (less than 2%). The digraph frequencies of words and pseudowords are also quite small (6%). However, as intended, the recombination of letters produced nonwords with a much lower average digraph frequency than that of the other two categories (30% lower). Finally, all three stimulus categories differ at the trigraph level.

Method

The experiment was done on a Hazeltine 1500 terminal controlled by a PDP 11/45 computer. Each trial was initiated by an auditory signal (a "beep"). Two hundred milliseconds later, a stimulus string was displayed for one second in the center of the CRT. 1.7 seconds after the disappearance of the string, the typist heard two short bursts of white noise through a speaker sitting on the terminal, separated by 700 msec. These were followed, another 700 msec later, by a tone. A high tone (500 Hz) informed the typist to type the stimulus string "as fast and accurately as possible." The characters typed were not displayed on the CRT, but characters, the time between the onset of the tone and the first keystroke, and the subsequent interstroke intervals were all recorded. On about 23% of the trials a low tone (150 Hz) signaled the typist to ignore the stimulus string and wait for the next trial. These catch trials were to prevent the typist from beginning before hearing the tone. Another trial began 3 seconds after the subject's last keystroke (or after the low tone on catch trials). Each stimulus string was presented once to each typist, with the allocation of a given string to test or catch trial varying with typist.

Table 1

Single Letter, Digraph and Trigraph Frequency Totals for the Stimuli Used in the First Study

	Words	Pseudowords	Nonwords
Single Letter			
1H	9987	9845	9938
2H	9931	9938	10110
Mean	9959	9892	10024
Digraph			
1H	839	783	604
2H	726	693	469
Mean	783	738	537
Trigraph			
1H	70	55	25
2H	67	49	20
Mean	69	52	23

The experiment required four sessions per typist, each lasting less than an hour and held on different days. The first sessions were practice sessions, in which the typing speeds of the typists were estimated by having them transcribe one page of English prose on the terminal keyboard. Each subsequent session followed the procedure described above and consisted of three blocks of trials: one of words, one of pseudowords, and one of nonwords. Word length and catch trials were randomized within each block. The order in which blocks were presented varied both over sessions and over typists. There were 12 practice trials at the beginning of each block and error trials were repeated at the end of the block.

Four right-handed typists participated in the experiment. Their range was from 65 to 73 words per minute, averaging 70 (171 msec/keystroke).

Results

Table 2, summarizes three aspects of performance: the latency preceding the first keystroke, the average interstroke interval, and the percentage of errors. Each 1H and 2H entry is based on around 90 trials per subject, 0.2% of the trials having been eliminated because the latency was longer than 3 seconds and/or one or more of the interstroke intervals was longer than 2 seconds.

The results of primary interest are the mean interstroke intervals. An analysis of variance revealed a significant stimulus category effect, $F(2,6) = 12.59$, $p<.01$. Further comparisons showed that the effect is limited to the difference between the nonwords and the other two categories, $F(1,6) = 24.6$, $p<.01$. The 3 msec difference between the words and the pseudowords is not significant, $F(1,6) < 1$. In short, the pattern of interstroke intervals reflects the digraph composition of the stimulus. This is true within each motor composition set (1H and 2H) as well as overall, with the interaction between the stimulus category and the motor composition of the strings yielding an F ratio smaller than 1.

The constancy of interstroke interval across words and pseudowords is not achieved by increasing the preparation time and delaying the execution of the first keystroke for pseudowords. The 6 msec difference shown in Table 2 is not statistically significant, nor is the 23 msec difference between the nonwords and the other two stimulus categories (both $F < 1$).

Finally, the typists do not sacrifice accuracy to achieve comparable speeds in typing the words and pseudowords. The 1% difference in average error rate between these two categories is not significant, $F(1,6) < 1$. However, there is a significantly higher error rate typing nonwords than the other stimulus types, $F(1,6) = 41$, $p<.001$. No interaction is significant. In short, the error rates parallel the temporal results.

Table 2

Latencies, Average Interstroke Intervals and Error Rates Obtained in the First Study

	Words	Pseudowords	Nonwords
Latency			
1H	405	397	426
2H	447	443	455
Mean	426	420	441
Interstroke Interval			
1H	183	185	196
2H	123	126	139
Mean	153	156	168
Percent Error			
1H	4.9	7.1	11.8
2H	5.7	5.7	9.4
Mean	5.3	6.4	10.6

Discussion

The results just presented are in total disagreement with the findings of Sternberg, Knoll, and Wright (1978): (a) In their study, words produced shorter interstroke intervals than any nonlexical letter strings, while in our study words and pseudowords were identical; (b) Among their nonlexical strings, there was no digraph frequency effect, while we found a difference between pseudowords and nonwords.

It is unlikely that the small procedural differences between the two studies can account for the differences in results. Indeed, other variables such as string length and motor composition produced very similar effects in both studies (see Larochelle, in press, for a detailed discussion of these results). Since the only major discrepancies between the two studies concern these frequency effects on performance, differences in the orthographical composition of the stimulus strings may be responsible.

1. Sternberg, Knoll, and Wright did not equate their words and pseudowords for digraph composition. Therefore, the faster interstroke intervals obtained with words could very easily reflect a difference in average digraph frequency between these two types of stimuli. Our results clearly show that the words lose their advantage over nonlexical strings when the digraph frequency is controlled.

2. The frequency effect between pseudowords and nonwords that we found, but Sternberg, Knoll, and Wright (1978) did not find, may stem from "illegal" digraphs in our nonwords. Sternberg et al. reported using low-frequency but not zero-frequency or "illegal" digraphs. In addition, our stimuli comprise 22 different letters used equally often (a, z, x, and c were eliminated because there are no letters in the corresponding position on the other side of the keyboard), while their nonlexical strings are constructed from a basic set of 16 letters, which may not have occurred equally often in their high and low frequency strings.

However, the issue of the presence (or absence) of digraph frequency effects in the typing of nonsense strings becomes of limited interest once it is established that there are digraph frequency effects in the typing of words (where all the digraphs are by definition legal). This is what the next study demonstrates.

One last important inference may be drawn from this study. We did not maintain equivalence of words and nonlexical strings at the trigraph and higher order levels; thus, the nearly identical results with words and pseudowords strongly suggests that these levels of organization do not contribute significantly to typing performance in the discontinuous typing situation.

Although past experiments have typically revealed differences between words and nonlexical strings in continuous (transcription) typing, the nonlexical strings used were probably not equated with the words in terms of digraph frequency. And in any case, the discontinuous typing paradigm was developed to minimize the influence of perceptual aspects of typing. Performance differences in continuous and discontinuous typing situations could reflect the contribution of higher level structure (from trigraphs to words) to perceptual processes rather than to the execution of the typing response per se.

The Digraph Frequency Effect

Fox and Stansfield (1964) found no effect of digraph frequency after separating sequences into 1H and 2H categories, avoiding the confounding of frequency with handedness. However, this categorization retains a lot of noise, since even among within-hand digraphs there can be a great deal of variability in the distance a finger or the hand must move. To control fully for such physical effects, we isolated all digraphs that appeared in both orderings of the letter sequence in the text to be transcribed (described below). Thus, th (as found in the), and ht (as in weight); ed (as in learned), and de (as in ride). There are 129 such sets. If there is a digraph frequency effect, we expected the interstroke interval to be shorter for the higher frequency ordering of the letters.

This analysis prevents the confounding of 2H with high-frequency digraphs from having any effect. If a digraph is 2H, the digraph made by reversing the order of the letters is 2H as well. It also minimizes other constraints imposed by keyboard layout, and physical constraints, such as the distance a finger or hand most move between successive keystrokes. We have isolated matched pairs of digraphs that should share virtually everything except digraph frequency. For the single-finger (1F) example de, the distance that the finger must move to reach the e after striking the d is the same as to reach the d from the e in ed. However, digraph frequency is uncontrolled -- in this case, ed occurs twice as often as de. For 2F sequences such as ta and at, postural and coordination constraints tend to be balanced. If more subtle constraints influence the typing of 2H sequences such as th and ht, they, too, tend to be balanced. Context may selectively constrain the typing of one of the two digraphs, but over the entire set this should be independent of digraph frequency.

Method

Six professional typists transcribed a magazine article of approximately 12,000 characters on a Microswitch keyboard designed to look and feel identical with the IBM Selectric typewriter keyboard with which the typists were familiar. The text was presented as double-spaced typed copy on individual sheets of paper. After a 10 minute warmup with another text, the typists were given the article and asked to type it rapidly, correcting errors only if they felt more comfortable doing so. Keypresses and the corresponding times were recorded by a microcomputer.

Because there are large individual differences among typists (Gentner, 1981a), the data for each typist were analyzed separately. For each letter pair, the median interstroke interval was determined. The value for the higher-frequency ordering was then subtracted from the value for the lower-frequency pair. We refer to this difference as the "Digraph Frequency Effect" (DFE). If higher frequency digraphs are typed faster, the DFE should be a positive number.

Consider as an example the digraph ed and its reverse de, where ed has a higher frequency of occurrence than de. The Digraph Frequency Effect (DFE) is the facilitation in the interkeystroke interval for the second letter of the more frequent digraph (i.e., the d of ed) over the interkeystroke interval required for the second key of the reverse digraph (i.e., the e in de). More generally, for any characters a and b with the frequency of ab greater than ba:

DFE = (interval for a in ba) - (interval for b in ab).

For one typist, the median interval to the e in de is 189 msecs, and the median for the d in ed, the more frequent of the two digraphs, is 168 msecs. For this example, then, there is a DFE of 21 msecs.

Two measures of digraph frequency were used -- the frequency as found in the text, and the frequency reported by Mayzner and Tresselt (1965: they examined a corpus of 20,000 words). For 29 of the 129 sets the two measures differed. Although the Mayzner and Tresselt (MT) data are probably more reliable, short-term exposure effects might be detected using the text frequencies.

Results

Every typist is on the average faster with the higher-frequency pairs. Using the text statistics there is an average difference of 10.0 msecs; using the MT norms it is 13.0 msecs. (The median interstroke interval for these typists is about 150 msecs.) Using the MT measure, the DFE ranges from 19.0 $\pm$ 7.4 msecs for Typist 4 to 8.6 $\pm$ 6.8 msecs for Typist 5 ($p < .05$ for each with a one-tailed t-test). Using text frequency, the effects were smaller, and for one typist (Typist 5) not significantly different from zero. These data are presented in the first two rows of Table 3.

Further Analysis

These data are subject to possible nonrandomness in the language and keyboard layout. The analysis does not distinguish between sets in which one or both digraphs are very common and sets in which both digraphs have low rates of occurrence. Also, it does not consider the magnitude of the frequency difference between the two digraphs within a set. Lumped together are the sets ga and ag, with frequencies of 7 and 6 in the text, and al and la, which have frequencies of 114 and 32.

Accordingly, we established criteria for selecting a more homogeneous subset. We used the rule that one of the two digraphs had to be encountered 100 or more times in the text and there had to be at least a 2-1 differential between the more common and less common of the two digraphs. For example, al and la, with text frequencies of 114 and 32, qualified. The first criterion insured that one digraph was well-practiced; the second criterion prevented both items from being almost equally practiced, and thus perhaps equally well-coordinated. There were 16 such sets.

Although this sample is much smaller than that in the previous analyses, the results of this analysis are cleaner (see the third row of Table 3). The DFE averages 15.9 msecs, and the mean variance is significantly smaller. The DFE is different from zero with probability $p < .05$ for all six typists.

In most of these pairs the first letter in the higher-frequency ordering was usually typed by a more peripheral finger, such as the little finger. To eliminate the possibility that the result was simply an effect of finger, we next isolated pairs in which the higher-frequency digraph began with a more central finger, or in which both letters were typed by the same finger. Twenty-five such items also had a moderate overall frequency and an approximately 2-1 (or more) differential between frequency of the two orderings.

Again there is a significant, if significantly smaller, DFE. The mean saving is 8.5 msec (see the first row of Table 4). The smaller effect indicates a probable influence of the fingers involved. However, the digraph frequency effect predominates.

Table 3

Time Saved Typing Second Letter of Higher-Frequency Digraphs (msecs)

		Typist						
		1	2	3	4	5	6	mean
Freqs from text used in study (n = 124)	mean	12.8**	10.4**	12.8*	17.1**	3.2	3.9*	10.0
	SD	48.5	39.8	57.3	42.7	38.6	30.5	42.9
Freqs from Mayzner & Tresselt (n = 128)	mean	15.0**	15.5**	10.7*	19.0**	8.6**	9.4**	13.0
	SD	50.8	37.7	60.8	42.8	39.1	30.6	43.6
Items with high freq disparity (n = 16)	mean	18.0**	13.9*	21.5*	23.9*	9.6*	8.5*	15.9
	SD	20.7	30.2	47.5	48.8	20.0	17.6	30.8

* $p < .05$ that the mean = 0.0
** $p < .01$

Table 4

Time Saved Typing Second Letter of Higher-Frequency Digraphs (msecs)

	Typist						
	1	2	3	4	5	6	mean
Same finger or toward periphery (n = 25)	8.0*	6.1	11.0*	18.7*	5.5	1.8	8.5
HF digraph: first letter HF (n = 56)	17.0*	18.0**	2.0	10.9*	8.1*	5.8	10.3
HF digraph: first letter LF (n = 73)	13.4*	13.6**	18.7*	25.2**	8.9*	12.2**	15.3

* $p < .05$ that the mean = 0.0
** $p < .01$

A final analysis eliminated the possibility that the DFE is due to a simple letter frequency effect. We separated the pairs according to whether the first letter in the higher-frequency digraph is itself a higher or a lower frequency letter. As indicated in the second and third rows of Table 4 , there is a sizable DFE in both cases, with the difference insignificant.

Discussion

These analyses demonstrate that digraph frequency in the language has a bearing on the interval between the typing of the two letters. Words are probably not simply decomposed into individual letters.

An easy way to check whether the effect is due to physical factors such as key and finger placement or is due to higher order units (as we propose) is to examine how the Rumelhart and Norman typing simulation model deals with these digraphs. Remember, the model successfully accounts for the major phenomena of skilled typing, but it uses only single letter response units. We therefore performed the same analyses on the data for the same text generated by the simulation model. The model did not show any effect of digraph frequency (higher-frequency pairs were an insignificant two msec slower).

We cannot absolutely attribute the frequency effect to performance variables. Low-frequency digraphs tend to occur in low-frequency words, and it could be that a differential ease of perception is involved. However, our first study, as well as other studies of transcription typing (e.g., Gentner, Grudin, & Conway, 1980; Gentner, 1981a) suggest that limiting factors in typing are on the motor output side, not on the perceptual side. Therefore, it is worth considering how motor facilitation might occur.

Lundervold (1951) recorded EMGs in a typing task. He found that motor activity typically begins proximally, or in muscles closer to the body, and that finger motion begins later. Activity in postural muscles of the back and shoulder precedes the upper arm muscle activity that accompanies the keystroke. In addition, substantial, regular motor activity follows each keystroke, as the finger and hand are retracted from the key.

Lundervold did not extend his analysis to the level of individual fingers. But handling multi-letter sequences as units could lead to better coordination of postural adjustments and the sequencing of flexion (keystroke) and extension (withdrawal) activity. Such increased coordination would particularly aid in 2F sequences, where the movements toward successive keys are most likely to conflict.

Table 5 presents the frequency data broken down to show the facilitation for 1F, 2F, and 2H digraphs. The facilitation is stronger for 2F digraphs overall, despite Typist 5, whose atypical performance is discussed below. This is a further assurance that the frequency effects are motor, rather than perceptual. There is no reason to expect a

Table 5

Time Saved Typing Second Letter of Higher-Frequency Digraphs (msecs)

	Typist						
	1	2	3	4	5	6	mean
2H Digraphs (n = 70)	7.7*	10.6*	4.6	16.6**	12.0**	5.0	9.4
2F Digraphs (n = 48)	27.5**	25.5**	22.2*	20.6**	2.9	16.3**	19.2
1F Digraphs (n = 11)	8.1	3.2	-5.3	27.0*	9.2	7.5	8.3

* $p < .05$ that the mean = 0.0
** $p < .01$

perceptual effect to be influenced by the mapping between letters and the hands that type them.

Videotape Analysis

Previous analyses of videotapes and a high-speed film of Typist 6 (Gentner, Grudin, and Conway, 1980; Gentner, 1981a) showed that finger movements toward successive keys frequently overlap in time, but that there are large individual differences in several aspects of skilled performance.

Informal viewing of the videotapes suggests how more efficient execution could arise from treating a sequence of two or more letters as a unit. For example, a typist can twist or rotate the hand above the keyboard and accomplish two things simultaneously. In typing the sequence _at_, a clockwise turning can lift the little finger from the _a_ while bringing the index finger toward the _t_.

The mechanism we focused on involves the retraction of the hand and fingers following the striking of a key. Most accounts of skilled typing have not emphasized that approximately half of the movement involved is that following the actual keystroke. For most typists the retraction is usually stronger than the downstroke. The movement toward a key is often initiated well in advance and carried out slowly. After the keystroke the finger and hand typically jerk sharply away from the keyboard. In his electromyographic investigation of typewriting, Lundervold (1951) recorded a great deal of activity in both postural muscles and in extensor muscles of the arm following each keystroke. The videotapes confirm this activity.

The regularity of the retraction suggests that it has a purpose. Possibly the use of the extensors and inhibition of the flexor muscles prevents perseverative activity by the finger that was just most active. Nevertheless, a strong retraction can work against the typist. If successive keys are being typed by the same hand, then when the hand pulls up from the keyboard after the first keystroke, the finger descending for the second must work against the upward movement of the hand. The finger travels a greater distance than it would have had the hand not retracted. We observed that some typists avoid this by not retracting the first finger until after the second key has been struck. This seemed particularly clear in common 2F sequences such as _er_, _re_, _ion_, _you_.

To establish that this delay in retraction is occurring, we selected sequences falling at the end of words, in particular _ion_ and _iet_. The question asked was: When does the right middle finger pull up from the _i_ key after striking it? In the sequence _iet_ the right hand need be in no hurry, since both _e_ and _t_ are typed by the other hand. (See Figure 1.) In the sequence _ion_ both letters following _i_ are also typed with the right hand.

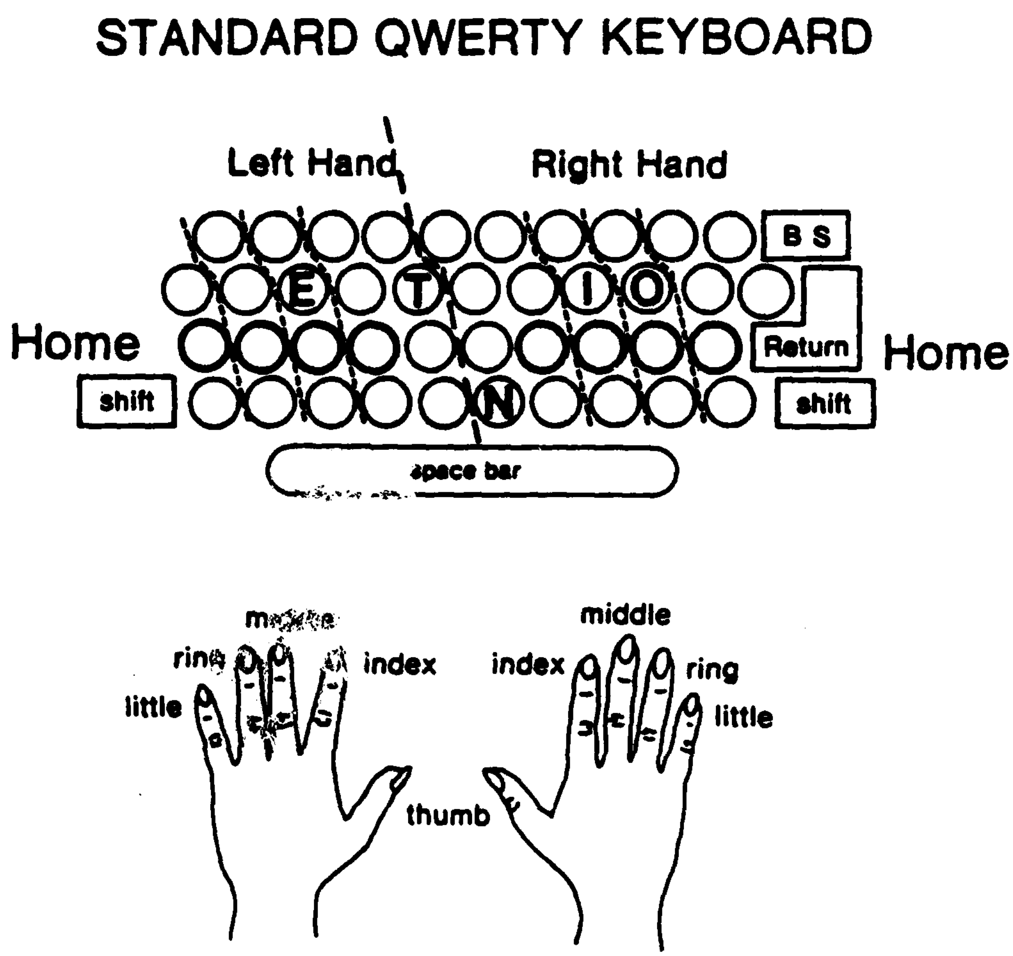

Figure 1. The typewriter keyboard. The sequence ion is typed with the middle, ring, and index fingers of the right hand. The letters e and t are typed with the left hand.

Method

The six typists were videotaped using a rotary shutter camera aimed down at the keyboard from above and behind the typist. Two views of the fingers were obtained by placing a mirror behind the keyboard at a 45 degree angle. By forming its image in less than two msec, the rotary shutter yields an image quite free of blur. The video fields were serially numbered with an electronic video counter and analyzed using a Sony video motion analyzer.

We looked at the first four instances of the typing of each sequence by each typist. The instant at which a keystroke occurred was indicated by a light-emitting diode on the keyboard, giving a time resolution of 16 msec (one video field). Retraction was defined to be the lifting of the finger from the key. (When withdrawal is delayed there is often a barely perceptible upward movement of the hand, not sufficient to lift the finger from the key.) The view across the top of the keys shown by the mirror allowed the withdrawal of finger from key to be determined to within one video field (16 msec).

Results

In the sequence ion, where retraction after typing the i might delay typing of the o or n, the mean time to onset of retraction of the middle finger is 135 msecs (8.1 videotape fields). The middle finger usually stayed down until one or both of the next two keys were struck. In the sequence iet the mean time to begin withdrawing the finger is 85 msec, or 5.1 fields (see Table 6).

There was relatively little within-typist variability. An analysis of variance indicated that the retraction times for the two sequences are different ($F(1,5) = 9.2$, $p < .05$). For four of the six typists, the ranges of withdrawal times did not overlap for ion and iet. The variance among typists was significantly greater than the error variance ($F(5,30) = 11.7$, $p < .001$).

Individual differences were, in fact, readily apparent from viewing the tape. Typist 1 always kept her right middle finger on the i in ion until the o and n were struck. Typist 5 lifted that finger and the right hand after the letter was typed independently of the context, and she showed no effect at all. One typist kept the i finger down until the o was struck, but lifted it before the n, while the other three typists sometimes held it down through the o and other times held it down for both o and n. Typist 3, for example, was extremely regular in typing iet, retracting finger and hand within 50 msec. With ion he held it down around 75 msec half the time and for over 140 msec the other times.

Table 6

Mean Time to Initiation of "i" Finger Retraction (msecs)

	Typist					
	1	2	3	4	5	6
letter sequence						
ion	200	150	117	104	71	167
iet	92	113	46	83	75	104

Discussion

The examination of other sequences, as well as Lundervold's (1951) EMG data, indicate that retraction of a finger within 100 msecs is typical when the hand is subsequently free. Thus, the delay observed in ion for withdrawing the i finger apparently results from the anticipated conflict such a movement would create with the striking of o and n. This example demonstrates that coordination of a commonly encountered sequence might improve performance.

It does not seem likely that the effect results from cancellation of the upward movement of the hand (withdrawal from the i) by the downward motion toward the o. Three typists appear to vary the number of keystrokes for which the delay is maintained, and in addition withdrawal is typically a stronger and more brief movement than that of striking a key. It seems that one action is being suppressed to facilitate later movement.

This is surely not the only means of coordinating multi-letter sequences. The existence of a frequency effect for 2H digraphs suggests that other factors are involved, and elsewhere we present evidence for across-hand response units (Grudin, 1981). This example only emphasizes that the digraph frequency effect can have motor origins, and suggests an approach to identifying some multi-letter response units in transcription typing.

Individual Differences

The major disparity among the typists is the performance of Typist 5. She shows the smallest frequency effects overall. She retracts her hand quickly following each keystroke, independent of the context. And unlike the other typists, she shows almost no facilitation for high-frequency 2F digraphs.

These results may explain why this typist types 2F and 1F digraphs at nearly the same speed (as reported by Gentner, 1981a). By retracting the hand following the first of two keystrokes on that hand, she delays the arrival of the second keystroke.

Rumelhart and Norman (1982) compared the output of their simulation model with the interstroke interval data of these six typists. Their model, based on single-letter response units, matches the performance of Typist 5 better than it matches any other typist. And the model is poorest in predicting the performance of Typists 1 and 4, who seem to show the strongest frequency effects.

Although the model shows no frequency effects, it does incorporate the effects of context and the physical constraints of the hands and the keyboard. Its generally good performance may reflect the relative importance of these factors. For example, when successive keys are typed by different hands, there can be greater overlapping of movement (Gentner, Grudin, & Conway, 1980). Looking at 33 pairs of digraphs

matched for frequency, we found that the interstroke interval for 2H digraphs averaged 45.6 msecs less than the interstroke interval for 2F digraphs. This is three times the magnitude of the frequency effects.

Implications

The video analysis suggests that the units of intermediate length are not just decomposed into individual letter units. Frequent sequences are not simply typed more frequently; adjustments are made early to facilitate activity coming later. It seems likely that a digraph or trigraph "unit" is not simply an association or strengthened linking of components.

Nor is it that individual keypress schemata work in parallel, producing coarticulation effects. In the suppressed retraction following a keystroke, something was added to the multi-character response unit that was not part of the individual single-letter responses formed early in the development of the skill. Experience with frequent sequences occasions the replacement of a small repertoire of simple response units by a larger repertoire of more complex but more efficient response units.

Multi-letter response units are not as difficult a step for the nervous system as it might seem. Lundervold's (1951) EMG data indicate that even a single keypress requires coordinated movement over more than 100 msecs, involving a number of postural muscles as well as those directly responsible for the final motion. Extending this pattern of activity to cover two or three keystrokes may not be difficult. First, the total time span may not change much, since the experienced typist is typing more rapidly. In addition, the postural adjustments that Lundervold and others (Lee, 1980) found to be an integral part of movement, often preceding overt action, may be simplified by considering a sequence in its entirety.

A final consideration is the size of the multi-letter response units. Although Terzuolo and Viviani (1980) argued that motor units exist for entire words, Gentner (1981b) has shown that their findings result in part from an artifact of their scaling procedure, and in general fail to withstand statistical scrutiny. Nevertheless, some common trigraphs and short function words very likely exist as response units. However, there is some evidence that the two-character response unit is the largest that is frequently employed.

In our first study, we found that performance in a discontinuous typing task is not impaired for pseudowords relative to words if the overall digraph frequency is unchanged. Overall trigraph frequency is considerably lower for the pseudowords, yet typists are not affected. However, if single-letter frequency is preserved but digraph frequency lowered, performance deteriorates.

Rabbitt (1978) asked typists to stop typing when they noticed making an error and found that most typists sometimes type one additional letter before stopping. A second additional letter is rarely typed. Among the errors made by skilled typists, we find numerous two-letter insertions, omissions, and even substitutions, but almost no three-letter errors. Elsewhere, we note that when an error spans more than two characters, it is usually of a nature to suggest an error across units (Grudin, 1981).

The frequency effect suggests that multi-letter units develop with practice, and fewer trigraphs than digraphs are encountered often. There are 96 digraphs but only 20 trigraphs with a frequency of one in every 100 words in the Mayzner and Tresselt (1965) corpus, and 156 digraphs and 67 trigraphs with a frequency of one in every 200 words.

Moreover, given that most of the advantage of high-frequency digraphs is for 2F sequences, there would be diminishing benefit in lengthening the motor sequences to form trigraphs. Only one-fourth of all trigraphs are within-hand. Still, response units of three or more letters may be formed -- the video evidence for the sequence ion suggests that sometimes it is treated as a unit. And the timing data show a small frequency effect for across-hand sequences, which could contribute to the efficiency of other three-letter sequences.

In summary, the faster typing of higher-frequency digraphs is best explained by the formation of multi-letter response units. These units can be more than strengthened associations of individual letter response sequences. Early movements are adjusted to facilitate later action in a sequence. Thus, these longer output sequences may eventually supplement or partially replace the initial, single-letter motor patterns. The presence of such units may explain much of the variability in typing that is not accounted for by the constraints of context, keyboard layout, and the hand.

References

Beeching, W.A. Century of the typewriter. New York: St. Martin's Press, 1974.

Bryan, W.L., & Harter, N. Studies in the physiology and psychology of telegraphic language. Psychological Review, 1897, 4, 27-53.

Bryan, W.L., & Harter, N. Studies on the telegraphic language. Psychological Review, 1899, 6, 345-375.

Estes, W.K. An associative basis for coding and organization in memory. In A.W. Melton & E. Martin (Eds.), Coding processes in human memory. Washington, D.C.: Winston, 1972.

Fox, J.G., & Stansfield, R.G. Digram keying times for typists. Ergonomics, 1964, 7, 317-320.

Fromkin, V.A. The non-anomalous nature of anomalous utterances. Language, 1971, 47, 27-51.

Gentner, D.R. Skilled finger movements in typing (Tech. Rept.). La Jolla, Calif.: University of California, San Diego, Center for Human Information Processing, 1981a.

Gentner, D.R. Timing patterns in typing. Manuscript in preparation, 1981b.

Gentner, D.R., Grudin, J.T., & Conway, E. Finger movements in transcription typing (Tech. Rept. 8001). La Jolla, Calif.: University of California, San Diego, Center for Human Information Processing, 1980.

Grudin, J.T. The organization of serial order in typing. Unpublished doctoral dissertation, University of California at San Diego, 1981.

Keller, F.S. The phantom plateau. Journal of Experimental Analysis of Behavior, 1958, 1, 1-13.

Larochelle, S. A comparison of skilled and novice performance in discontinuous typing. In W.E. Cooper (Ed.), Cognitive aspects of skilled typing. New York: Springer-Verlag, in press.

Lashley, K.S. The problem of serial order in behavior. In L.A. Jeffress (Ed.), Cerebral mechanisms in behavior. New York: Wiley, 1951.

Lee, W. The neuromuscular pattern of rapid arm flexion under choice reaction time conditions. Unpublished doctoral dissertation, University of Texas at Austin, 1980.

The LNR Research Group: Gentner, D.R., Grudin, J., Larochelle, S., Norman, D.A., & Rumelhart, D.E. A glossary of terms including a

classification of typing errors. In Studies of typing from the LNR Research Group: The role of context, differences in skill level, errors, and hand movements, and a computer simulation. In W.E. Cooper (Ed.), Cognitive aspects of skilled typing. New York: Springer-Verlag, in press.

Lundervold, A.J.S. Electromyographic investigations of position and manner of working in typewriting. Acta Physiologica Scandinavica, 1951, 24, supplementum 84.

Mayzner, M.S., & Tresselt, M.E. Tables of single-letter and digram frequency counts for various word-length and letter-position combinations. Psychonomics Monograph Supplement, 1965, 1, 13-32.

Rabbitt, P. Detection of errors by skilled typists. Ergonomics, 1978, 21, 945-958.

Rumelhart, D.E., & Norman, D.A. Simulating a skilled typist: A study of skilled cognitive-motor performance. Cognitive Science, 1982, in press.

Shaffer, L.H., & Hardwick, J. Typing performance as a function of text. Quarterly Journal of Experimental Psychology, 1968, 20, 360-369.

Sternberg, S., Knoll, R.L., & Wright, C.E. The timing of rapid movement sequences in typewriting. Paper presented at the meeting of the Psychonomic Society, San Antonio, Texas, 1978.

Terzuolo, C.A., & Viviani, P. Determinants and characteristics of motor patterns used for typing. Neuroscience, 1980, 5, 1085-1103.

Wickelgren, W.A. Context-sensitive coding, associative memory, and serial order in (speech) behavior. Psychological Review, 1969, 76, 1-15.

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CHIP Technical Report List

1. David M. Green and William J. McGill. On the equivalence of detection probabilities and well known statistical quantities. October, 1969.
2. Donald A. Norman. Comments on the information structure of memory. October, 1969.
3. Norman H. Anderson. Functional measurement and psychophysical judgment. October, 1969.
4. James C. Shanteau. An additive decision-making model for sequential estimation and inference judgments. October, 1969.
5. Norman H. Anderson. Averaging model applied to the size-weight illusion. October, 1969.
6. Norman H. Anderson and James C. Shanteau. Information integration in risky decision making. November, 1969.
7. George Mandler, Richard H. Meltzer, Zena Pearlstone. The structure of recognition. Effects of list tags and of acoustic and semantic confusion. November, 1969.
8. Dominic W. Massaro. Perceptual processes and forgetting in memory tasks. January, 1970.
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13. A.D. Baddeley and J.R. Ecob. Reaction time and short-term memory: A trace strength alternative to the high-speed exhaustive scanning hypothesis. November, 1970.
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15. Roy D. Patterson. Residue pitch as a function of the number and relative phase of the component sinusoids. March, 1971.
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17. David E. Rumelhart, Peter H. Lindsay, and Donald A. Norman. A process model for long-term memory. May, 1971.
18. David E. Rumelhart and Adele A. Abrahamson. Toward a theory of analogical reasoning. July, 1971.
19. Martin F. Kaplan. How response dispositions integrate with stimulus information. August, 1971.
20. Martin F. Kaplan and Norman H. Anderson. Comparison of information integration and reinforcement models for interpersonal attraction. August, 1971.
21. David M. Green and R. Duncan Luce. Speed-accuracy tradeoff in auditory detection. September, 1971.
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23. Norman H. Anderson and Arthur J. Farkas. New light on order effects in attitude change. March, 1972.
24. Norman H. Anderson. Information integration theory: A brief survey. April, 1972.
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35. Kent L. Norman. A method of maximum likelihood estimation for stimulus integration theory. August, 1973.
36. Yaakov Kareev. A model of human game playing. August, 1973.
37. Donald A. Norman. Cognitive organization and learning. August, 1973.
38. The Center for *Human Information Processing:* A Five Year Report — 1968-73.

39. Larry D. Rosen and J. Edward Russo. Binary processing in multi-alternative choice. October, 1973.

40. Samuel Himmelfarb and Norman H. Anderson. Integration theory analysis of opinion attribution. December, 1973.

41. George Mandler. Consciousness: Respectable, useful, and probably necessary. March, 1974.

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Arthur J. Farkas and Norman H. Anderson. Input summation and equity summation in multi-cue equity judgments. December, 1974.

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66. Vladimir J. Konečni. Some social, emotional, and cognitive determinants of aesthetic preference for melodies in complexity. December, 1976.

67. Hugh Mehan, Courtney B. Cazden, LaDonna Coles, Sue Fisher, Nick Maroules. The social organization of classroom lessons. December, 1976.

67a. Hugh Mehan, Courtney B. Cazden, LaDonna Coles, Sue Fisher, Nick Maroules. Appendices to the social organization of classroom lessons. December, 1976.

68. Norman H. Anderson. Integration theory applied to cognitive responses and attitudes. December, 1976.

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Norman H. Anderson and Clifford H. Butzin. Children's judgments of equity. June, 1977.

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86. Edited by Michael Cole, Edwin Hutchins, James Levin and Naomi Miyake. Naturalistic problem solving and microcomputers. Report of a Conference. June, 1979.

87. Donald A. Norman. Twelve issues for cognitive science. October, 1979.

88. Donald A. Norman. Slips of the mind and an outline for a theory of action. November, 1979.

89. The Center for Human Information Processing: A Description and a Five-Year Report (1974-1979). November, 1979.

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91. James L. McClelland and David E. Rumelhart. An interactive activation model of the effect of context in perception. Part I. April, 1980.

92. James L. McClelland and J.K. O'Regan. The role of expectations in the use of peripheral visual information in reading. February, 1980.

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94. Friedrich Wilkening and Norman H. Anderson. Comparison of two rule assessment methodologies for studying cognitive development. June, 1980.

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